# Coolant Leak from ISS External Active Thermal Control System (EATCS) – An Examination of Most Probable

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**The Port (P1) and Starboard (S1) External Active Thermal Control Systems (EATCS) are single phase, mechanically pumped ammonia loops that operate independently to cool majority of the hardware and payloads onboard the International Space Station (ISS). A slow ammonia leak was detected using pressure and quantity telemetry five years after the P1 EATCS was activated. The leak gradually accelerated to a rate that locating and isolating the leak became imperative to maintain cooling capability. Partial pressure measurements from the Robotic External Leak Locator (RELL) scan surveys narrowed the search to the supply and return jumpers connecting one of three radiators to the system. Subsequently, the ISS crew performed high definition video surveys during an Extravehicular Activity (EVA), or spacewalk, and ammonia flakes were observed projecting from the jumpers. Thus, the ground teams were confident that the culprit of the ammonia leak were the jumpers. The ammonia leak stopped after ground teams remotely isolated and vented those jumpers and associated radiator. Both jumpers were removed and returned to the ground, and a root cause investigation was conducted. A calibrated leak test determined the bulk of the ammonia leaked through a pair of seals in a Quick Disconnect (QD), or connector, on one end of the return jumper. The return jumper QD was dissected, visually inspected, chemically tested and evaluated. The results indicated the most probable cause of the accelerating ammonia leak was due to defective seals, plating delamination underneath the seals, and on-orbit thermal cycles exacerbating the delamination. Both jumpers were refurbished, relaunched to the ISS, and scheduled to be reinstalled during an EVA in 2022. It appeared the issue was unique, but recently the S1 EATCS is showing signs of an accelerating ammonia leak, and RELL scans narrowed the source to a similar pair of radiator jumpers.**

## Nomenclature

| | | |
|---|---|---|
| $GN_2$ | = | Gaseous Nitrogen |
| *kg* | = | kilogram |
| *kPa* | = | kilopascals |
| *lbm* | = | pound mass |
| $NH_3$ | = | ammonia |
| $NH_4OH$ | = | ammonium hydroxide |
| *ppm* | = | parts per million |
| *psia* | = | pound force per square inch |
| *sccs* | = | standard cubic centimeters per second |
| *ATCS* | = | Active Thermal Control System |
| *CT* | = | Computerized Tomography |
| *EATCS* | = | External Active Thermal Control System |
| *EDS* | = | Energy Dispersive X-Ray Spectroscopy |
| *EVA* | = | Extravehicular Activity |
| *FT-IR* | = | Fourier Transform Infrared |
| *fwd* | = | Forward |
| *ISS* | = | International Space Station |
| *JSC* | = | Lyndon B. Johnson Space Center |
| *LEO* | = | Low Earth Orbit |
| *M&P* | = | Materials and Processes |

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| | | |
|---|---|---|
| *MMOD* | = | Micrometeoroid and Orbital Debris |
| *NASA* | = | National Aeronautics and Space Administration |
| *NDE* | = | Nondestructive Evaluation |
| *NVR* | = | Non-volatile Residue |
| *P1* | = | Port 1 |
| *QD* | = | Quick Disconnect |
| *RBVM* | = | Radiator Beam Valve Module |
| *RELL* | = | Robotic External Leak Locator |
| *S1* | = | Starboard 1 |
| *TIM* | = | Technical Interchange Meeting |

## I. Introduction

The Port (P1), or Loop A, and Starboard (S1), or Loop B, External Active Thermal Control Systems (EATCS) are single phase, mechanically pumped ammonia loops that operate independently to cool majority of the hardware and payloads onboard the International Space Station (ISS). Five years after activation, the P1 EATCS experienced an accelerating coolant leak until it was stopped in 2017. A series of on-orbit activities narrowed down the leak source to a pair of supply and return jumpers that supply coolant to and from one of three P1 EATCS radiators. This radiator was isolated but reduced the cooling capability on the P1 EATCS. There were no spare jumpers on-orbit or on the ground to regain the capability, and further leaks could have jeopardized the sustainability of the ISS.

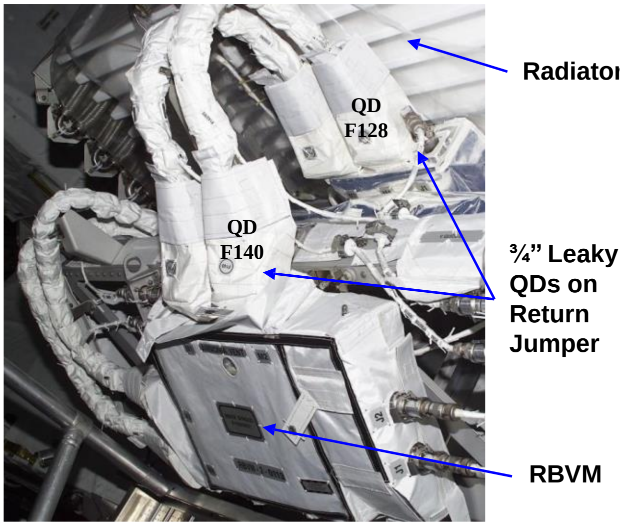

**Figure 1. Radiator Jumper connected to a radiator and the Radiator Beam Valve Module (RBVM) that control flow to and from the radiator**

Therefore, both jumpers were returned to the ground to be refurbished. During the refurbishment, a special calibrated leak test was performed on both jumpers. The found the highest leakage coming from a pair on seals inside the one of the two radiators return jumper Quick Disconnects (QD), QD F128[1]. These pair of seals can only be accessed by dissembling the QD. There are over two hundred QDs between the S1 and P1 EATCS, and twenty-four are on similar radiator return jumpers.

Founding out if the failure that caused QD F128 to leak if unique or common to all the other QDs was important to assess the long-term sustainability of the EATCS. Therefore, the QDs on the radiator return were removed, dissembled, and further evaluated to determine the most probable root cause of the leak. This paper discusses the finding, conclusions, recommendations, and observations from this investigation. The QDs on the return jumper were replaced with pristine QDs, and both supply and return radiator jumpers were refurbished. They were launched to the ISS and will be reinstalled during an Extravehicular Activity (EVA), or spacewalk, in March 2022.

## II. ISS External QD Overview

Quick Disconnects (QD) are used throughout the EATCS to connect hardware (i.e., pumps or radiators) to fluid lines and allows the hardware to removed or replaced by the crew. Generally, replaceable hardware like the radiator jumpers contain female QDs that mate to male QDs on the fluid lines like shown in figure 2. Inside each QD are seals to secure the male and female connection, allow ammonia to pass through, and prevent ammonia from leaking to space. There are various sizes, or diameters, QDs and over two hundred QDs between the P1 and S1 EATCS.

Parker Symetrics partnered with NASA to design and produce all the ISS EATCS QDs. The QD frame is made of stainless steel and Inconel, and some of the components are coated with nedox, a nickel-based coating. There are primary and secondary seals on the forward and aft end of each QD as shown in figure 6 and 5, respectively. The seals are made from a plastic material and spring loaded to handle the ammonia pressure load.

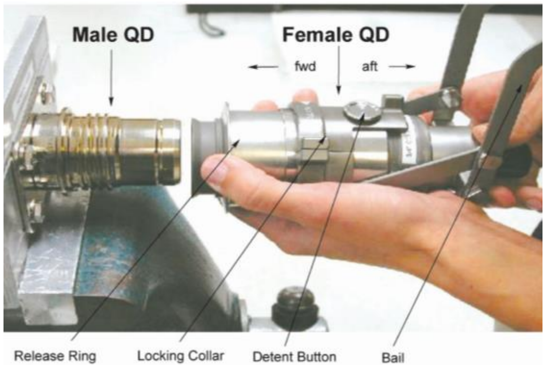


**Figure 2. Male and Female Quick Disconnects**

Several tests were performed during the development of QDs that verified the design and material are compatible with ammonia and would minimize leakage. The QDs were qualified to operate and cycle between temperatures and pressures of -100 and 155 Deg F (-148 to 68 Deg C), and 30 to 500 psia (207 and 3447 kPA). All the radiator return jumper QDs on the S1 and P1 EATCS experience temperature and pressure swings of -40 and 0 Deg F, and 100 and 390 psia (689 and 2689 kPa) while in service on-orbit. The allowable leakage of the QD seals is $10x^{-4}$ standard cubic centimeters (sccs) at nominal operating conditions, but well performing QDs would leak less than $10x^{-5}$ sccs based on ground development testing.

If a QD fails the leakage requirement during build, typically cleaning or replacing the primary and secondary forward seals will remedy the issue. Those seals are easily assessable during final assembly unlike the primary and secondary aft seals that are only assessable when the QD is disassembled. The acceptance leak test involves bagging the entire QD rather than separating the QD in half like performed on the leaky QD[1]. The risk of passing the leak test with possible underperforming primary and secondary aft seals was accepted since they would be inspected during the build.

## III. Failure Investigation Plan and Fishbone Diagram

NASA partnered with the ISS prime contractor, Boeing, and the QD manufacture Parker Symetrics to determine the most probable root cause of the leak of QD F128. A fishbone diagram was created to list the potential contributors to the leak as shown in figure 3. The failure investigation plan involved assessing each of the potential contributor through visual inspection, chemical evaluations, nondestructive evaluation (NDE), and destructive evaluations. First the QDs were disassembled by Parker Symetric and inspected by the naked eye and under magnification using a borescope and a stereo microscope. Material samples were then taken by NASA Johnson Space Center (JSC) and

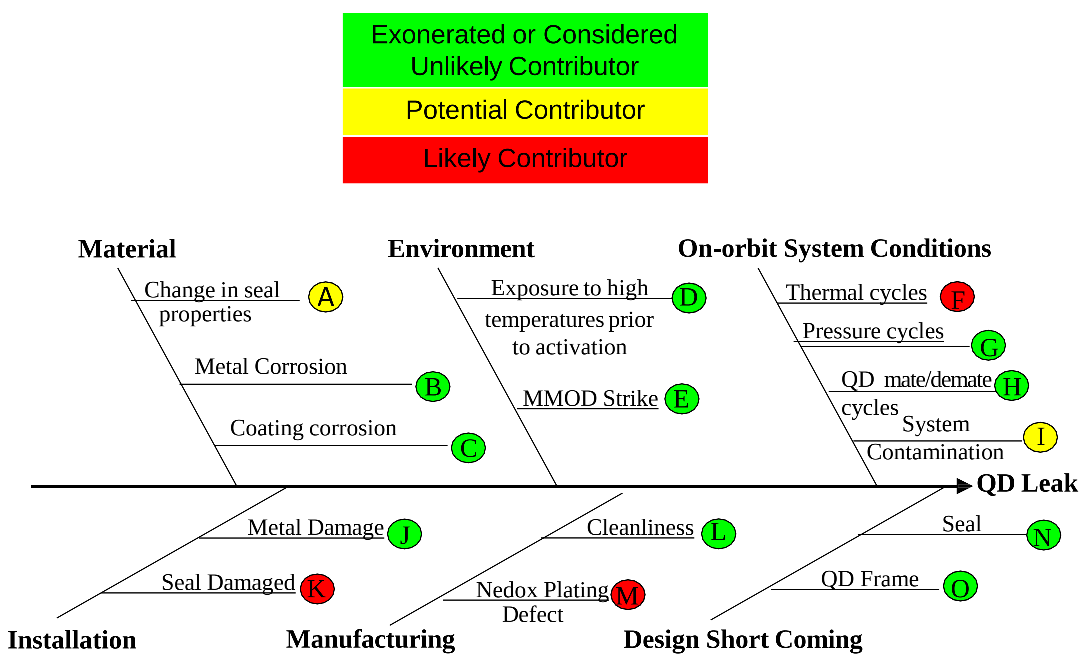


**Figure 3. Fishbone Diagram of Potential Contributors to the QD leak**

Boeing Huntsville Materials and Process (M&P) labs and evaluated using Energy Dispersive X-Ray Spectroscopy (EDS), Fourier Transform Infrared (FT-IR) and Computerized Tomography (CT) scanning to the determine any abnormalities.

An ammonia immersion test was performed at NASA's White Sands Test Facility (WSTF) to evaluate the non-volatile residue (NVR)[1] found on the QDs. Stereo microscopy was performed on the disassembled QDs following the immersion test, then the seals were removed. Finally, compression testing, Gas chromatography–mass spectrometry (GC-MS), and Differential Scanning Calorimetry (DSC) testing was performed on the seals, and the results were compared to a pristine seal to the determine any change to the material or fluid properties. The likelihood of each potential causes contributing to the QD leak is discussed in the next section of this paper.

## IV. Findings

### A. Exonerated or Considered Unlikely Contributors to the QD Leak

Bones B through E, G through H, J, L, and M through N shown in figure 3 were exonerated or considered unlikely a contributor to the QD leak. The QDs are made of 15-5 stainless steel and Inconel 718 with thick walls. Any cracks to the material because of corrosion, installation issues or collisions with Micrometeoroid and Orbital Debris (MMOD)[3] could cause a leak. However, this was not observed from the imagery inspections or chemical evaluations. Prior to when the radiators were filled with ammonia and the EATCS were activated in 2006, all the radiator jumper

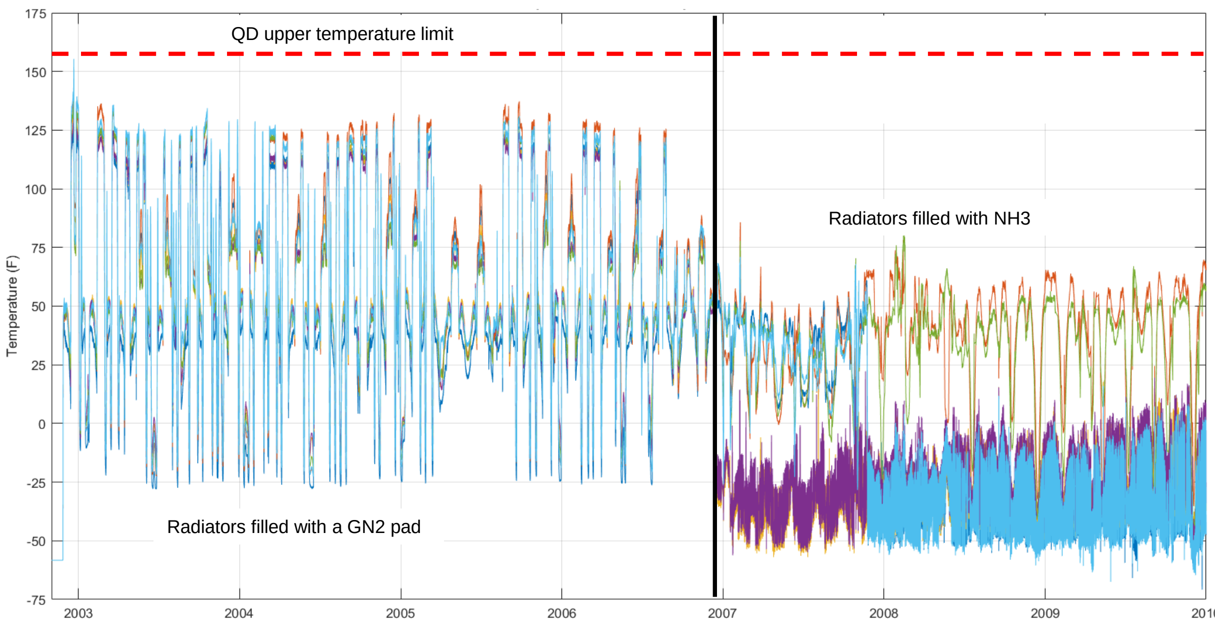


**Figure 4. Temperatures from each of the P1 EATCS radiators. Radiators were filled with GN2 until Mid 2006 then filled with ammonia and activated.**

QDs were exposed to temperatures higher than operating temperatures for a short period of time as shown in the figure 4. However, the temperatures did not exceed the QD upper temperature limit of 155 Deg F (68 Deg C), and was not expected to cause any damage.

The QDs are also exposed pressure swings, but a telemetry review concluded that that they were within the pressure limits. Some components of the QDs are plated with nedox. QD development testing has shown that nedox is expected to be resistant to corrosion when exposed to ammonia, but it is not resistant to ammonium hydroxide ($NH_4OH$) solutions. The corrosion mechanism of the nickel to form nickel oxide requires the presence of oxygen. Furthermore, high oxygen concentrations in ammonia is required for the nickel to nickel oxide reaction to progress and to corrode the nedox.

The ammonia in the P1 EATCS was purified with less than 20 parts per million, ppm, of oxygen, which is less than the 50 ppm needed to produce ammonium hydroxide and corrode the nedox in the QDs. In addition, sections of the QDs are exposed to the vacuum environment on-orbit. The Low Earth Orbit (LEO) environment of ISS is mainly

comprised of atomic oxygen[2], or O3. This is three times the atoms needed to produce ammonium hydroxide and corrode the nedox. Therefore, there isn't significant amount of O2 present in ammonia or the LEO environment to cause Nedox corrosion. The seals inside the QDs slide back and forth on the sealing surface when QDs are mated or demated.

Repeated cycling the QDs, or mating/demating, could degrade the seals and increase the risk of leakage. All the EATCS QDs were qualified to 100 mate and demate cycles, and the QD that leaked on-orbit only experienced 3 mate/demate cycles. In addition, the surfaces of the QDs were cleaned to requirements like MIL-STD-1246 Level 200F[4] that removed particulates and NVR prior to launch. Several tests were performed that verified cleaning to this level is sufficient and prevent contamination when wetted with ammonia. Therefore, it's unlikely that QD cycling, or cleanliness were a contributor to the QD leak.

The P1 and S1 EATCS have been operating and flowing with ammonia since 2006, and all the radiator jumper QDs experience the same thermal and pressure cycles. No other accelerating leaks have been detected from telemetry at the time of this investigation, which implies that there are no QD design short comings. NDE and destructive evaluation was performed on the leaky QD with the seals intact and removed to determine any changes to material and fluid properties or degradation. Results from the CT scanning showed a 10% decrease in the average seal dimension but results from the CT and DSC testing showed no significant change in material or fluid properties. Thus, no clear sign of seal degradation that could cause leaks to develop and implies there are no design short comings.

## B. Likely and Potential Contributors to the QD Leak

### B.1. Contributor K – Seal Defect During Installation

There are female QDs on the radiator return jumpers. QD F140 connects to the system and QD F128 connects to the radiator as shown in figure 1. There are primary and secondary seals located on the forward and aft end of each QD as shown in figure 6 and 5, and the calibrated leak test showed the highest leakage near the aft seals on QD F128[1]. After the QD was disassembled, stereo microscopic images found what appeared to be probable installation defect, or kink, on both aft seals on QD F128 as shown in figure 5. The defect goes across the seal in the direction that would allow ammonia to leak to the outside environment. A pristine seal would not have this defect as shown in figure 5, and this defect was not observed on any of the other seals in QD F128 or F140.

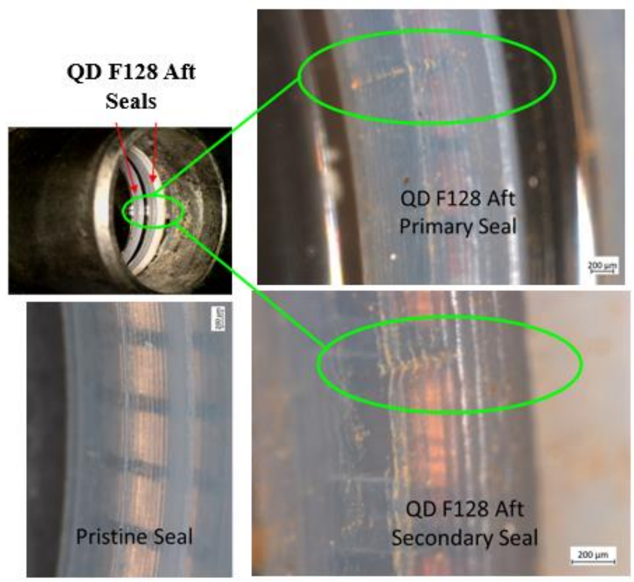


**Figure 5. QD F128 Aft Seals Defect Compared to a pristine Seal (QD).**

Such defects are common during installation and generally are replaced during inspection prior to launch. In addition, the QD would fail the leakage required during acceptance testing if any defects are missed. Processing records show that QD F128 failed the leakage requirement during final leak testing before launch. The QD passed the leakage requirement after the primary and secondary forward seals were replaced; the aft seals were not replaced since this would require disassembly of the QD. This leak test included the entire QD since the aft seals were not individually verifiable, which is an accepted risk for all QDs.

Ammonia would have to breach the primary and secondary aft seals to leak out to space. Since the calibrated leak test during the failure investigation showed the highest leakage coming from the aft seals and defects were found on seals, the failure assessment team concluded that at least one of these two aft seals had to have been performing well at time to pass the leak test prior to launch. The other seal could have been performing well or underperforming, which would be undetectable without dissembling the QD. Therefore, the aft seal defects were likely a contributor to the leak of QD F128.

### B.2. Contributor I - Fluid System Contamination

During visual inspections as part of the failure investigation before the QS was disassembled on the ground, brown NVR[1] was found on the secondary forward seals on both QD F128 and F140 as shown in figure 6. Chemical evaluations determined the amount was consistent with what is allowed in the ammonia per requirements[1]. Seal leakage over time can deposit NVR on the surfaces on and downstream the seal when exposed to vacuum. As ammonia leaks to space, the NVR would deposit on the cold surfaces as the ammonia vaporizes when exposed to vacuum Testing have shown that NVR will adhere to cold surfaces, and the radiator return QDs are exposed to -40 to 0 Deg F (40 to -18 Deg C) while in service on-orbit..

NVR deposits might not necessarily impact seal performance but could cause problems for valve cycling (mate/demate). It is expected that these NVR may also reside on the sealing surfaces on the male QDs on-orbit that mate with QD F128 and F140, and could cause problems securing a proper seal when they are mated. Theoretically, soaking the male QD with ammonia could dissolve the NVR and clean the seal surfaces. However, this process would have to be performed during the EVA that will install the refurbished jumpers in March 2022 since the jumpers need to be in place to send ammonia to the male QDs.

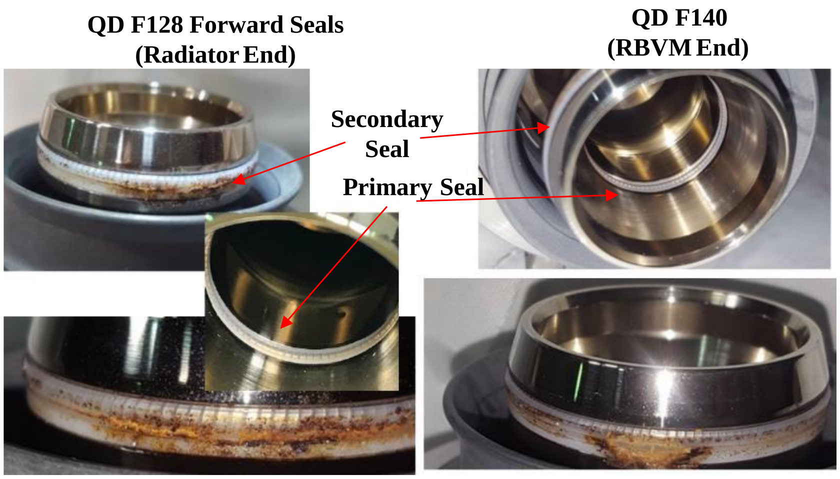


**Figure 6. Brown NVR shown on the QD F128 and F140 Secondary Aft Seals**

To evaluate this, the failure investigation team performed an ammonia immersion test on the leaky QD to determine if the deposits would dissolve back into solution and how long this process would take. The test included soaking the disassembled QD with ammonia for increasing durations, and the final test point included agitation. The results found that the NVR did not readily dissolve back into solution and would take several hours. This is longer than the amount of time available during the EVA to install the refurbished jumpers. Therefore, soaking the male QDs during the EVA would not be beneficial.

**B.3. Contributor M- Nedox Plating defect**

Stereo microscope imagery was performed on the leaky QD following the ammonia immersion test, and nedox plating delamination was found on the sealing surface. This location happens to coincide with the location of defect found on the aft seals on QD F128 as shown in figure 7. Delamination wasn't observed prior to the ammonia immersion as it was hidden under areas with NVR. The consequences of nedox delamination can produce a path for ammonia to leak to space especially if it's located underneath a seal; ammonia would pass under the seal through the delaminated area.

Therefore, this was likely a contributor to the QD leak. Nedox adhesion issues were observed during ground acceptance testing of two similar radiator return QDs and were from the same lot of the leaky QD F128; delamination

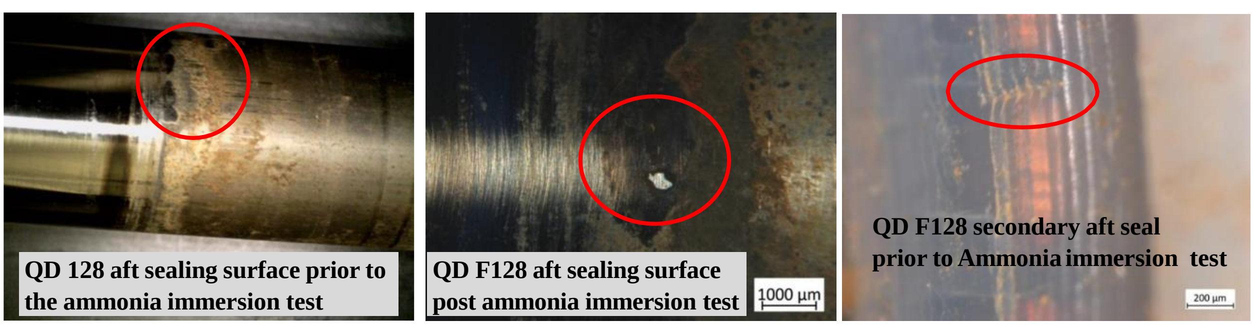


**Figure 7. QD F128 sealing surface prior (left image) and after (middle image) of the ammonia immersion test. Defect found on the aft seal (right image) coincides with delaminated area (middle image)**

was not observed on the ground on QD F128. The lot includes all the radiator return jumper QDs currently on-orbit and on the five spares on the ground. In 2000, NASA M&P led an evaluation of the issue with the vendor, Parker Symetrics, and determined that the likely cause of the delamination was due to contamination of surfaces on a few components during plating.

At the time, the experts believed this issue was not fleet wide, and the delamination was localized to those two QD, which were later scrapped. The other radiator jumper QDs, including F128, were already installed and prepared for launch when the issue was discovered. It was recommended at the time that re-inspecting the remainder of the lot was not required as it was believed that delamination would be detected during acceptance testing like the two that were scrapped. However, the plating processes were modified to help make this issue less likely to occur.

### B.4. Contributor F - On-orbit Thermal Cycles

The nominal on-orbit operating temperature of the ammonia flowing through the all the radiator return jumper QD range from -40 to 0 Deg F (40 to -18 Deg C). Though this is well with the requirements of -100 and 155 Deg F (-73 and 68 Deg C), thermal cycling of this magnitude could aggravate the nedox delamination found on QD F128. Thus, cause the delaminated area to grow and leak more ammonia over time. This is likely why the P1 EATCS ammonia leak accelerated while the leaky QD F128 was in service before it was stopped in 2017 as shown in figure 8.

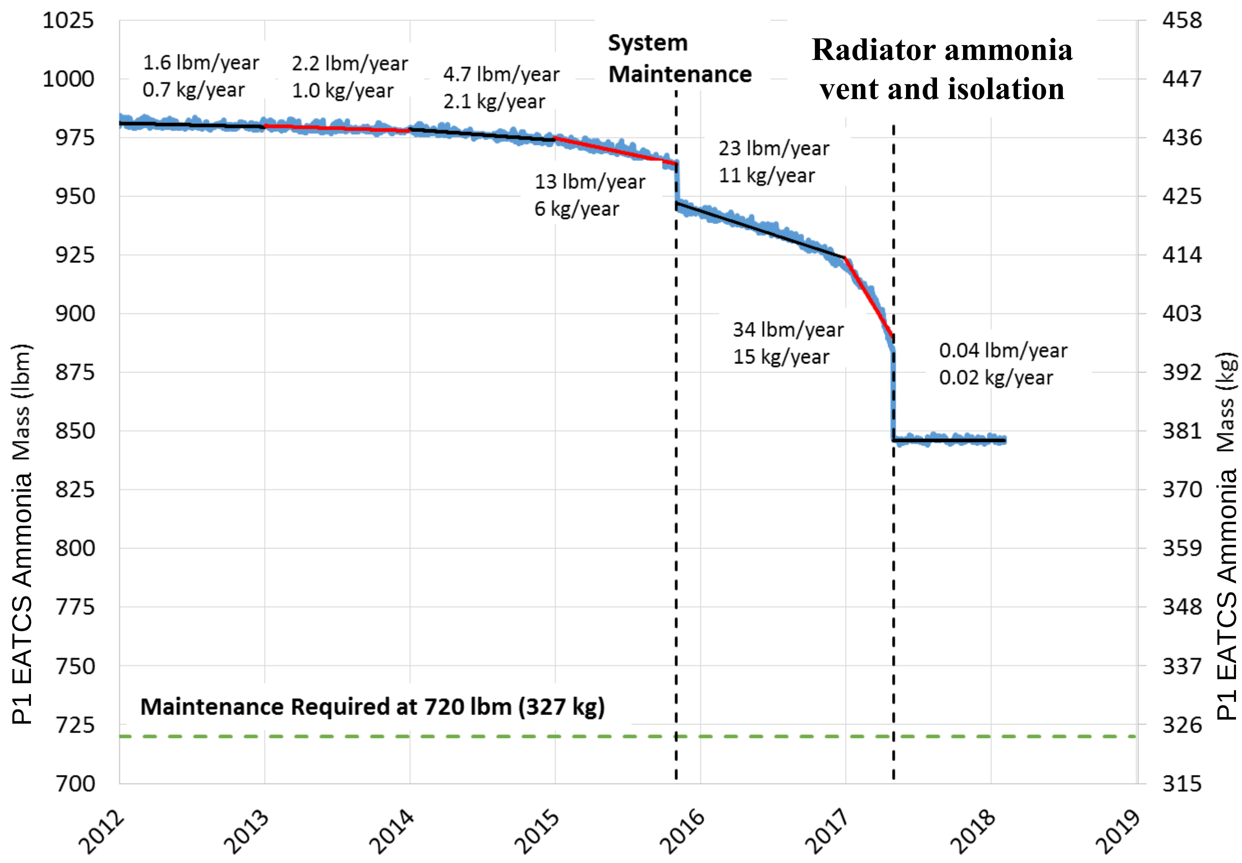


**Figure 8. P1 EATCS Calculated Ammonia Mass and leak rates from 2012 to 2018.**

## V. Conclusions

A Technical Interchange Meeting (TIM) was held with technical experts across the agency and contactors to review all the finds. It was concluded that there were multiple contributors QD leak, and the most probable root cause is a combination of the following:

1. The aft QD seals were possibly damaged during installation causing a defect, and likely one of the seals may never have sealed properly

2. Localized nedox plating adhesion issues which caused delamination and was coincidentally located underneath the defect found on the aft seals. Thus, introducing a leak path

3. Nominal on-orbit operating thermal cycles aggravated the nedox delamination causing the leak path to grow; thus, resulting in an accelerating leak rate

At the completion of this investigation, it was also concluded that this issue is likely unique to this QD. Though possible nedox adhesion issues may exist on all the EATCS radiator return jumper QDs, a defective seal and nedox plating delamination coinciding was believed less likely. In addition, all the other radiator jumper QDs have been in service for over fifteen years, and no other accelerating leaks have been detected on the S1 or P1 EATCS.

## VI. Recommendations

The following was recommended based on the conclusions:

1. Continue with the current sparing posture of the radiators jumpers and QDs
    a. There are no spare radiator jumpers on-orbit, but some parts are available to assemble one on the ground when necessary
    b. There are five spare radiator return jumpers QDs and it was recommended to use those QDs when necesary even though they are from the same lot as the leaky QD with the nedox adhesion issues; this amount of QDs likely sufficient to support any replacement through end of life of ISS

2. Verify the integrity of the refurbished jumpers
    a. During the EVA to reinstall the radiator jumpers, have the crew perform imagery inspections of the male QDs that will mate with the jumpers
        i. Though the radiator return jumper QD was replaced and passed leakage requirements on the ground, it’s expected that NVR is present on the male QDs that mate to them on-orbit
        ii. This may result in adequate sealing
    b. After the jumpers are installed and the radiator is refill with ammonia, perform Robotic External Leak Locator (RELL)[1] scans to evaluate any leaks

3. Continue using the current QD design
    a. On-orbit data indicates that other radiator return jumper QDs have not exhibited a similar leak; thus, the design is likely to perform satisfactorily when the seals are in good shape and the nedox coating is intact
    b. In addition, process improvements have already been implemented to prevent nedox plating issues found on the leaky QD with the current QD design

## VII. Observations

Following the conclusion of this investigation, telemetry from the S1 EATCS began showing signs of a possible accelerating ammonia leak. RELL scans were performed, and the results indicated that ammonia was originating from a similar radiator return jumper QD as the leak QD F128 on one of the S1 EATCS radiators. Recommendations from this paper should be considered in further evaluating the S1 EATCS leak.

## Acknowledgments

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Russell Morrison (Boeing QD Expert) and Johnny Golden (retired Boeing QD Expert) were significant contributors to this investigation.

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